Irrigation and tillage effects on soil nitrous oxide emissions in maize monoculture

Abbreviation

CIR, crop irrigation requirement; ETo, reference evapotranspiration; ETc, crop evapotranspiration; GMT, Greenwich Mean Time; WFPS, water-filled pore space.

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ABSTRACT

Irrigation and soil management can impact soil nitrous oxide (N_2O) emissions. Flood and sprinkler irrigation systems together with conventional tillage are the main practices used in the high yielding maize systems in Mediterranean Spain. The objective of this field work was to quantify the effect of the irrigation system (i.e. flood, F; and sprinkler, S) and the soil tillage system (i.e. conventional tillage, CT; no-tillage maintaining the maize stover, NTr; and no-tillage removing the maize stover, NT) on the N_2O emissions from the soil during three years (2015, 2016 and 2017). S irrigation, with mean values of 1.35 kg N_2O-N ha^{-1} $year^{-1}$ throughout the three years, obtained 42% lower N_2O emissions than F irrigation. On average of the three growing seasons, yield-scaled N_2O emissions by grain yield and by grain N uptake in F irrigation were two-fold higher than in S irrigation. Moreover, in one out of three growing seasons (2017), no-tillage systems (i.e. NTr and NT) showed greater yield-scaled N_2O emissions compared with CT. The higher maize grain yield with the S irrigation compared to F irrigation, as well as the lower N_2O emissions reported under S irrigation resulted in the reduction of the yield-scaled N_2O emissions. Our findings highlight the role of sprinkler irrigation decreasing N_2O emissions in comparison to flood irrigation in Mediterranean agroecosystems.

Agricultural management practices such as irrigation, stover management, tillage and nitrogen fertilization have an important role on soil greenhouse gas emissions (GHG) and particularly on N_2O emissions (Reay et al., 2012; IPCC, 2014). The production of N_2O in the soil is the result of the interaction between biotic and abiotic factors. Soil microbial communities throughout the nitrification, denitrification and nitrifier denitrification processes control soil N_2O production, which are influenced by the soil water-filled pore space (WFPS) (Bateman and Baggs, 2005; Bremner, 1997; Firestone and Davidson, 1989). Under aerobic conditions, when WFPS range between 35 to 60%, nitrification is the main process involved in the N_2O production. However, when WFPS is above 60% up to 80%, denitrification is the principal process responsible of N_2O production in the soil due to anaerobic conditions (Linn and Doran, 1984). In addition to biotic factors and WFPS, abiotic factors such as soil nitrate and soil ammonium contents, soil temperature and soil organic carbon are also key factors on the production and dynamics of N_2O in the soil (Davidson et al., 2000; Bouwman et al., 2002; Butterbach-Bahl et al., 2013).

Trost et al. (2013) in a review of eight studies around the world about the effect of irrigation on soil N_2O emissions reported that soil N_2O emission increased after irrigation because increased the WFPS. Moreover, in Mediterranean areas, several studies have concluded that irrigation is an important agricultural practice contributing to soil N_2O emissions (Aguilera et al., 2003; Cayuela et al., 2017; Sanz-Cobena et al., 2017). Similarly, Deng et al. (2018) evaluated the impact of the irrigation system on soil N_2O emissions for the California cropland using the DNDC model and predicted a reduction of 38% on soil N_2O emissions under sprinkler irrigation compared with flood irrigation.

Likewise, other studies reported different effects of tillage on soil N_2O emissions. For instance, Ball et al. (1999) and Venterea et al. (2011) observed an increase on soil N_2O emission under no-tillage. However, Ussiri et al. (2009) and Omonode et al. (2011)

reported lower emissions under no-tillage than under conventional tillage. In rainfed barley (*Hordeum vulgare* L.) monoculture in NE Spain, Plaza-Bonilla et al. (2018) recently observed a reduction on the N_2O emitted per unit of yield under no-tillage systems when compared to conventional tillage. This last work is in agreement with the results obtained by the same authors in a previous work (Plaza-Bonilla et al., 2014), in which they observed lower or similar emissions in no-tillage systems compared to conventional tillage systems, when no-tillage was performed for more than 10 years. However, in the first years after the implementation of no-tillage, they obtained higher emissions under no-tillage than conventional tillage, similar to the findings of Van Kessel et al. (2013).

Crop stover removal may influence soil microclimate conditions, favouring higher soil temperature and r soil water evaporation (Sauer et al., 1998). Additionally, a decrease on soil organic carbon (SOC) and a degradation of soil physical properties are associated with removing the stover from the field (Blanco-Canqui and Lal, 2008). Then, crop stover management could affect soil N_2O emissions, but their effect is no clear. Jin et al. (2017) observed higher N_2O emissions in irrigated maize when maize stover was maintained in the field. However, Bent et al. (2016) observed higher soil N_2O emissions when maize stover was removed in Ontario, Canada.

In Spain, maize is one of the main irrigated crops. Over the last 13 years, (2004-2017) maize accounted around 40% of the total irrigated cereal surface (MAPAMA, 2017b). Flood (F) and sprinkler (S) irrigation are the main irrigation systems used in Spain for maize with the 53% and 28% of the total maize irrigated surface through the period 2007-2017, respectively (MAPAMA, 2017b). In the last years, sprinkler irrigation of maize has significantly increased, due to the increase in crop yield and the automation of the irrigation (Playán and Mateos, 2006; Lecina et al., 2010). Moreover, in Spain, the adoption of no-tillage is low with only 10% of the total cereal surface and mostly under rainfed conditions (MAPAMA, 2017a).

In the last decade, several experiments have been carried out to study agronomical aspects of sprinkler irrigation systems regarding to the crop water requirements and crop performance under Mediterranean climatic conditions (Cavero et al., 2003; Robles et al., 2017; Cavero et al., 2018). However, limited studies have been done to assess the impact of different agronomical practices on N_2O emissions in Mediterranean climatic conditions under irrigation and mostly focused on nitrogen (N) fertilization management (Álvaro-Fuentes et al., 2016; Maris et al., 2018). Similarly, a limited number of studies have been conducted to compare the effect of different tillage practices on N_2O emissions in Mediterranean climatic conditions and all these studies were carried out under rainfed conditions (Plaza-Bonilla et al., 2014; Plaza-Bonilla et al., 2018).

This study was aimed to assess the impact of irrigation system, specifically sprinkler and flood irrigation systems, and the soil tillage system, conventional tillage and no-tillage systems, on soil N_2O emissions under Mediterranean climatic conditions. Since sprinkler irrigation allows to apply lower amounts of water at higher frequency than flood irrigation, we hypothesize that irrigation system would result in different soil water content during the growing season which would affect N_2O emissions and maize yields. Besides, given that tillage has also shown to affect N_2O emissions, we also hypothesize that irrigation system would interact with tillage.

MATERIAL AND METHODS

Site description

A field study was performed during three maize seasons (2015-2017) at the experimental farm of the Experimental Station of Aula Dei, Zaragoza, Spain (41º 42´ N, 0º 49´ W, 225 m altitude). The area is characterized by a Mediterranean semiarid climate with annual mean air temperature of 14.1 ºC, annual precipitation of 298 mm and grass reference crop evapotranspiration (ETo) of 1243 mm and silty loam soils (Table 1).

Table 1. Soil characteristics of the experimental field.

Depth	pH	SOC†	$CaCO_3$	Sand	Silt	Clay	FC‡	WP§
m		%					$m^3\ m^{-3}$	
0.00−0.05	7.98	1.93	34.9	15.7	61.9	22.3	0.26	0.14
0.05−0.10	8.20	1.85	34.9	15.4	62.9	21.7	0.26	0.14
0.10−0.25	8.03	1.75	35.1	15.9	62.1	22.0	0.25	0.16
0.25−0.50	7.95	1.51	35.3	16.0	63.6	20.3	0.25	0.16

† Soil organic carbon. ‡ FC, Field capacity (-0.033 MPa). § WP, Wilting point (-1.5 MPa).

Experimental design

Previously to the establishment of the experiment, the field had been under cultivation, alternating different cereal crops, mainly irrigated winter wheat (*Triticum aestivum* L.) and maize under conventional tillage and flood irrigation. The previous crop was winter wheat that was grown during one year (2014). In addition, this experimental field had the possibility to install a hand-move sprinkler irrigation system. Therefore, in 2015, the field was divided in two parts, one irrigated by flood irrigation and the other one by a hand-move sprinkler irrigation of 18 m × 18 m sprinkler square spacing and with a sprinkler application rate of 5 mm h^{-1}.

The experimental layout consisted on a split-block design with two factors and three replicates per treatment. Two irrigation systems (i.e. sprinkler, S, and flood, F) and three soil tillage systems (i.e. conventional tillage, CT; no-tillage maintaining the maize stover, NTr; and no-tillage removing the maize stover, NT) were combined obtaining six different treatments with a 6 x 18 m plot size.

In CT, tillage operations previous to maize sowing consisted in one pass of a subsoiler to 30 cm depth followed by one pass of a disk harrow both performed on December 2014, 2015 and 2016 and one pass of a rotary tiller just before maize sowing on April 2015, 2016 and 2017. No-tillage consisted in a total herbicide application (5 L glyphosate (36%)) before sowing. All tillage operations were made with commercial size machines. Maize cv. Pioneer P1785 was sown on 09 April 2015, 12 April 2016 and 17 April 2017 in rows 75 cm apart at a planting density of 89,500 plants ha^{-1}. Fertilizer operations were the same in all treatments consisting in one application of 800 kg ha^{-1} of a NPK (8 (ammonium N ($N\text{-}NH_4^+$))-15-15) compound fertilizer before planting on 09 April 2015, 12 April 2016 and 17 April 2017 and 740 kg ha^{-1} of calcium ammonium nitrate N-27% (13.5% ammonium N ($N\text{-}NH_4^+$) – 13.5 nitrate N ($N\text{-}NO_3$)) as top dressing (V6 – V8 growth stage) on 02 June 2015, 13 June 2016 and 07 June 2017. Harvest with a commercial combine was carried out on 30 September 2015, 5 October 2016 and 17 October 2017. The stover residue was chopped and spread over the soil by a chopper machine. Weed and pest control were carried out following the best management practices of the area. The crop stover of the NT treatment was removed manually on 23 December 2015, and 11 October 2016. Thus, the NT treatment was incorporated into the experimental design the second growing season (2016) after the 2015 harvest, when the crop residue was removed.

Maize daily crop evapotranspiration (ETc) was computed by multiplying the reference evapotranspiration (ETo), obtained by the FAO Penman-Monteith method (Allen et al., 1998), and the crop coefficient (Kc) determined using an equation developed in the same experimental farm based on a function of the thermal time (Kiniry, 1991; Martínez-Cob, 2008). Crop irrigation requirement (CIR) for each week was determined by subtracting the effective precipitation, 75% of the total weekly precipitation (Dastane, 1978), to the weekly ETc considering an irrigation efficiency of 85%. Irrigation water was applied by sprinkler irrigation to all the plots until V6 growth stage to favour plant emergence and to avoid differences in plant density among treatments.

Irrigation frequency depended on the irrigation system. Thereby, during the three growing seasons, sprinkler irrigation events occurred two times per week (Monday and Wednesday), whereas flood irrigation events occurred every 10-14 days. Although the sprinkler irrigation system allows applying an exact irrigation dose, this is not possible with flood irrigation. Thus, the irrigation water applied in the sprinkler system was each year within 2% of the CIR. However, the irrigation water applied in the flood system was 16% to 30% higher than in the sprinkler system (Table 2). Irrigation applied in the sprinkler system was measured with a flowmeter and in the flood system with a Cipolletti weir. All tillage treatments under the same irrigation system received the same amount of irrigation water.

Table 2. Calculated crop evapotranspiration (ETc), crop irrigation requirement (CIR) and irrigation water applied in both irrigation systems (sprinkler and flood) applied in the maize growing season of 2015, 2016 and 2017.

Season	ETc	CIR	Irrigation	
			Sprinkler	Flood
	mm			
2015	719	712	729	950
2016	763	722	708	824
2017	744	693	686	874

Air sampling and N_2O analyses

Two polyvinyl chloride (PVC) rings (31.5 cm internal diameter) per plot were inserted 10 cm into the soil on April 2015, before to start the soil gas measured. The rings were only removed at tillage, planting and harvesting operations. Soil N_2O emissions were measured with the closed chamber technique (Hutchinson and Moiser, 1981) from April 2015 to September 2017, using PVC chambers (20 cm height) covered with a reflective layer of aluminium film to diminish internal increases in temperature. On the center of the top of the chamber, a chlorobutyle septum was attached as a sampling port.

Soil N_2O emissions were measured weekly from planting until mid-August (VT growth stage), every two weeks from mid-August until harvest (late September) and every three weeks during the fallow period (October-March). During tillage operations, soil air samples were taken 24 h before, and 24 and 96 h after the tillage operations. Throughout the fertilization events, soil air samples were taken 24 h before and 24, 48, 72, 96, 144 and 192 h after fertilization. Finally, soil air sampling frequency was increased during the five days after of each irrigation event over the three growing seasons, in order to characterize the flood irrigation events.

Air samples were collected at 0, 20 and 40 min after chamber closure and 20 mL of air sample were transferred to an evacuated 12-mL Exetainer ® borosilicate glass vial (model 038W, Labco, High Wycombe, UK). Air temperature inside the chamber was measured introducing thermometers in the chamber before the enclosed of the chambers.

Concentration of N_2O in the air samples was measured by gas chromatography using an automatically injection system (PAL3 autosampler, Zwingen, Switzerland). The gas chromatography systems (Agilent 7890B, Agilent, Santa Clara, CA, United States) was equipped with an electron capture detector (ECD) and a HP-Plot Q column (15 m long, 320 μm in section and 20 μm thick), using He as a carrier gas at 2 mL min^{-1}. The injector and the oven temperatures were set to 50 and 35ºC, respectively. The temperature of the ECD was set to 280ºC and a 5% methane in Argon gas mixture at 30 mL min^{-1} was used as a make-up gas. Ultra-high purity N_2O standards (Carburos Metálicos, Barcelona, Spain) was used to calibrate the system. Emission rates (mg N_2O-N m^{-2} day^{-1}) were calculated by the linear increase in the N_2O concentration during the chamber enclosure time and corrected by the internal air chamber temperature.

Soil, biomass and grain yield sampling and analyses

Soil ammonium (NH_4^+) and nitrate (NO_3^-) contents were quantified on each air sampling date from the 0–5 cm soil layer by extracting 50 g of fresh soil with 100 mL of 1 M KCl. The extracts were frozen and later analysed with a continuous flow autoanalyser (Seal Autoanalyser 3, Seal Analytical, Norderstedt, Germany). Concentration values were transformed to kg N ha^{-1} using the soil bulk density and corrected by the soil moisture. Soil temperature and moisture content were measured using a Crison TM 65 probe (Carpi, Italy) and GS3 soil moisture probes (Decagon Devices, Pullman, WA), respectively. Volumetric soil moisture content and soil bulk density, measured once per month for each plot by the cylinder method (Grossman and Reinsch, 2002), were used to calculate soil water filled pore space (WFPS) assuming a soil particle density of 2.65 Mg m^{-3}.

Maize grain yield for each plot was determined by weighing the total grain harvested by a commercial combine and corrected to 14% moisture content. A grain subsample from each plot was dried at 60 ºC for 48 h and weighed to determine maize grain moisture. Afterwards grain subsamples were grinded and analysed to determine the N content by dry combustion (TruSpec CN, LECO, St Joseph, MI, USA).

Data analysis

Cumulative soil N_2O emissions on a mass basis (i.e., kg N ha^{-1}) were quantified using the trapezoid rule (Levy et al., 2017). Repeated measures analysis of variance (ANOVA) for logarithm transformed data of N_2O fluxes, soil NH_4^+ and NO_3^- content, and WFPS, and soil temperature were performed for sprinkler and flood irrigation and for 2015, 2016 and 2017 growing seasons (i.e. April - October) and for 15-16 and 16-17 fallow period (i.e. November – March) separately with soil tillage system, date of sampling and their interactions as sources of variation using the JMP 10 statistical package (SAS Institute Inc, 2012).

In addition, different ANOVA were performed for 2015, 2016 and 2017 growing seasons for cumulative N_2O emissions, grain yield, N uptake by the grain, grain yield N_2O scaled emissions and grain N-uptake N_2O scaled emissions with irrigation system, soil tillage system and their interactions as sources of variation. When significant, differences between treatment means were evaluated by Tukey test at 5% significance level. The relationships between soil N_2O flux and concentration of soil soil NH_4^+ and NO_3^-, WFPS and soil temperature was evaluated by the significance of Pearson coefficients by using JMP 10 statistical package (SAS Institute Inc., 2012).

RESULTS

Environmental conditions

Daily precipitation, mean daily air temperature and daily reference evapotranspiration, ETo, for the entire measurement period are shown in Fig. 1.

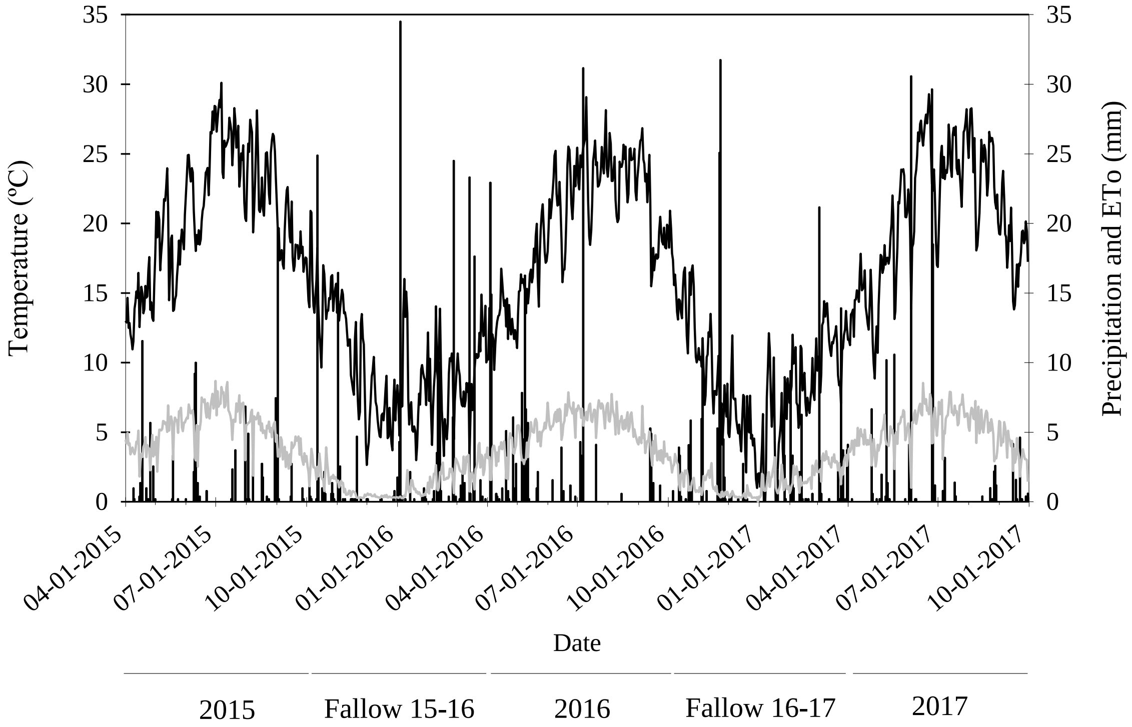

Figure 1. Air temperature (black continuous line), precipitation (vertical bars) and reference evapotranspiration (ETo) (grey continuous line).

On average throughout the maize growing seasons, air temperature was 21.9, 21.3 and 21.8ºC for 2015, 2016 and 2017 growing seasons (hereafter 2015; 2016; 2017), respectively. During the periods between growing seasons (i.e. fallow period), mean air temperature was 9.2 and 9.1ºC for fallow 15-16 and fallow 16-17, respectively. Total precipitation during fallow periods were 180 and 272 mm for fallow 15-16 and fallow 16-17, respectively. Whereas, during the growing seasons, total precipitation was 92 (2015), 111 (2016) and 139 mm (2017).

Soil WFPS, soil temperature and soil ammonium and nitrate content

Over the entire experimental time, WFPS was significantly affected by the interaction between tillage system and sampling date in both irrigation systems (Table 3, Fig. 2a and 2b). Under F irrigation, in which the crop irrigation requirement (CIR) of ten-fourteen days was applied in one irrigation event, large fluctuations on WFPS values were observed between two events. Before the irrigation event, WFPS values ranged between 20 and 30%, but during the 24 h after the irrigation event WFPS was close to 100% and decreased rapidly hereafter (Fig. 2b). In contrast, S irrigation showed steadier WFPS values, with average WFPS values of 46% throughout the three growing seasons and without reaching values higher than 80% WFPS (Fig. 2a).

Soil temperature was significantly affected by the interaction between tillage and sampling date in all measurement periods except during the fallow 15-16 for S irrigation (Table 3, Fig. 2c and 2d). Over the three growing seasons, mean soil temperature was 19.7 (2015), 17.7 (2016) and 18.2ºC (2017) in S irrigation, whereas under F irrigation mean soil temperature values were 19.4, 18.9 and 19.2ºC for 2015, 2016 and 2017 respectively.

Table 3 ANOVA (*p-value*) for soil water-filled pore space (WPFS) (0-5 cm), soil temperature (5 cm depth), and soil nitrate and ammonium content (0–5 cm) for sprinkler and flood irrigation as affected by tillage, date and their interaction over the different measurement periods.

	Period				
Variable and Effect	2015	Fallow 15-16	2016	Fallow 16-17	2017
			Sprinkler irrigation		
WFPS					
Tillage	*0.049*	*0.001*	*<0.001*	*0.047*	*<0.001*
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	*<0.003*	*<0.001*	*<0.001*	*<0.001*
Soil Temperature					
Tillage	*0.024*	NS	*<0.001*	NS	*0.032*
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	NS	*<0.001*	*0.008*	*<0.001*
Soil nitrate					
Tillage	NS	NS	NS	NS	*0.036*
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	NS	*0.016*	NS	*0.008*	*0.009*
Soil ammonium					
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	NS	NS	NS	NS
			Flood irrigation		
WFPS					
Tillage	NS	*<0.001*	*0.002*	*0.01*	*<0.001*
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	*<0.001*	*<0.001*	*0.008*	*<0.001*
Soil temperature					
Tillage	NS	*0.014*	*<0.001*	*<0.001*	NS
Date	*<0.001*	*<0.001*	*0.021*	*0.008*	*<0.001*
Tillage x Date	*<0.001*	*0.009*	*<0.001*	*0.003*	*<0.001*
Soil nitrate					
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	NS	*0.025*	*<0.001*	NS	NS
Soil ammonium					
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	NS	NS	NS	*0.006*

NS, non-significant

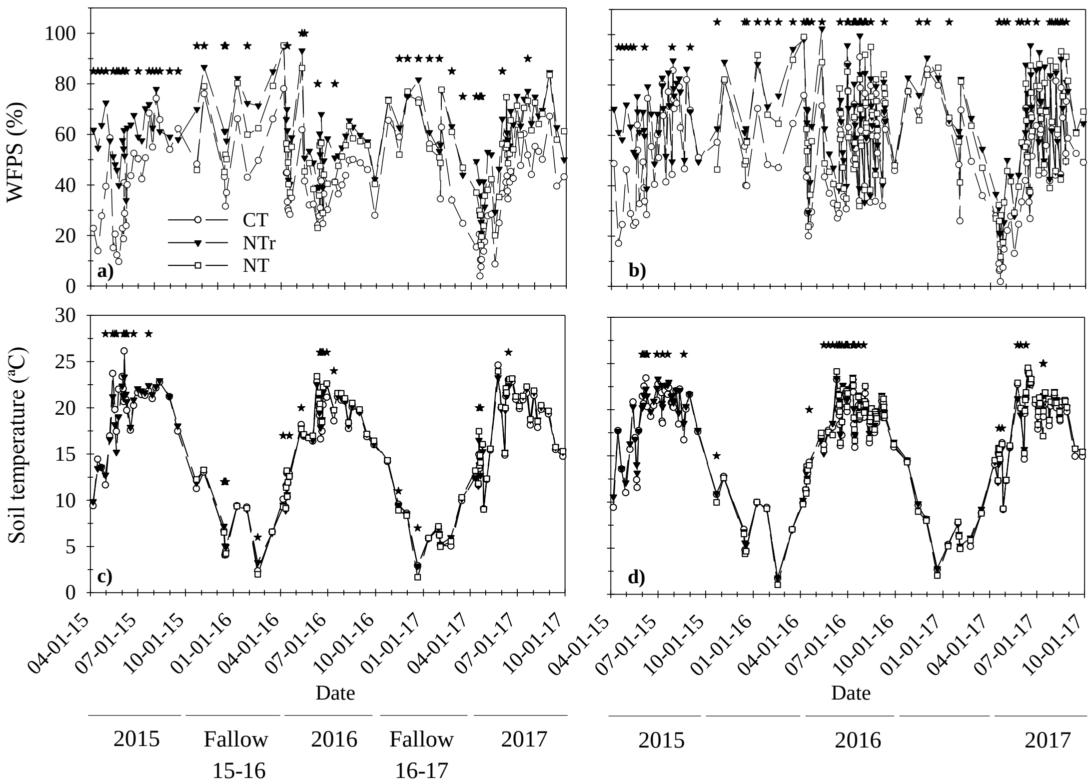

Figure 2. Soil water-filled pore space (WFPS) in the 0-5 cm depth and soil temperature at 5 cm depth for sprinkler (a, c) and flood (b, d) irrigated plots as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining maize stover), NT (no-tillage removing maize stover). *Indicates significant differences between treatments within a date at $p<0.05$.

In both irrigation systems, soil NO_3^- content (0-5 cm depth) increased after the pre-planting application of fertilizer for a period of 45 days. The maximum values were reached during the top dressing application (V6 growth stage) of nitrogen fertilizer and lasted 4 days, then soil NO_3^- content started to decrease (Fig. 3a and 3b). A significant interaction between soil tillage and sampling date was observed for both fallow periods and during 2017 under S irrigation, while under F irrigation the significant interaction between soil tillage and sampling date affected soil NO_3^- content in 2016 and fallow 15-16 (Table 3).

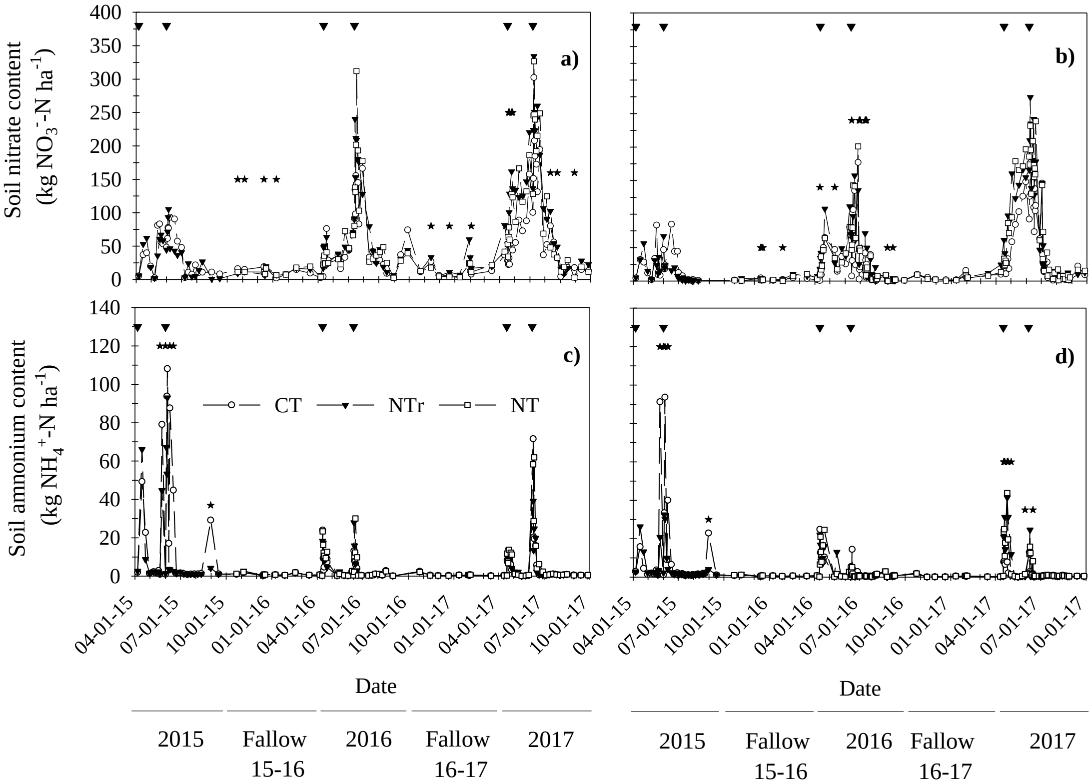

Figure 3. Soil nitrate content (NO_3^--N) (0-5 cm) and soil ammonium content (NH_4^+-N) (0-5 cm) for sprinkler (a, c) and flood (b, d) irrigation systems as affected by soil tillage system: CT (conventional tillage), NTr (no-tillage maintaining maize stover), NT (no-tillage removing maize stover). *Indicates significant differences between treatments within a date at p<0.05. Black triangles indicate N fertilizer applications.

Soil NH_4^+ content remained low during the most of the experimental time, showing a strong increase after the fertilizer applications (Fig. 3c and 3d). Under S irrigation a significant interaction between soil tillage and sampling date was observed in 2015, while under F irrigation the significant interaction between soil tillage and sampling date affected soil NH_4^+ content in 2015 and 2017 (Table 3).

Nitrous oxide emissions

In both irrigation systems, daily soil N_2O fluxes were significantly affected by the interaction between soil tillage and sampling date in 2016 and 2017 but not during 2015 nor in both fallow periods (Table 4). However, this interaction only occurred after each N fertilizer application. Under S irrigation, the interaction between soil tillage and sampling date was only observed in 34 and 12% of the sampling dates in 2016 and 2017, respectively. However, under F irrigation only 11 (2016) and 12% (2017) of the sampling dates showed significant soil tillage and sampling date interaction (Fig. 4).

Table 4. ANOVA (*p-value*) for the daily soil N_2O flux for sprinkler and flood irrigation over the different measurement periods as affected by soil tillage, sampling date and their interaction.

	Soil N_2O flux				
Effect	2015	Fallow 15-16	2016	Fallow 16-17	2017
			Sprinkler irrigation		
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	*0.017*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	NS	NS	*<0.001*	NS	*0.044*
			Flood irrigation		
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	NS	*<0.001*	*0.029*	*<0.001*
Tillage x Date	NS	NS	*0.034*	NS	*0.023*

NS, non-significant

For S irrigation the mean soil N_2O flux was 2.85 (2015), 0.85 (2016), 0.86 (2017) mg N_2O-N m^{-2} day^{-1}. For F irrigation the mean soil N_2O flux was 2.35 (2015), 2.77 (2016), 2.09 (2017) mg N_2O-N m^{-2} day^{-1}.

Soil daily N_2O fluxes were low during the most part of the entire measurement period (values lower to 1 mg N_2O-N m^{-2} day^{-1}). However, after fertilizer applications, soil N_2O flux peaks occurred, especially after top dressing applications of nitrogen fertilizers (Fig. 4). Under S irrigation, N_2O flux peaks after nitrogen applications reached values close to 15 mg m^{-2} day^{-1} in 2015, while in 2016 and 2017 the flux peaks dropped to 12 mg N_2O-

N m^{-2} day^{-1} (Fig. 4a). In contrast, under F irrigation, N_2O flux peaks measured ranged between 30 and 60 mg N_2O-N m^{-2} day^{-1} (Fig. 4b).

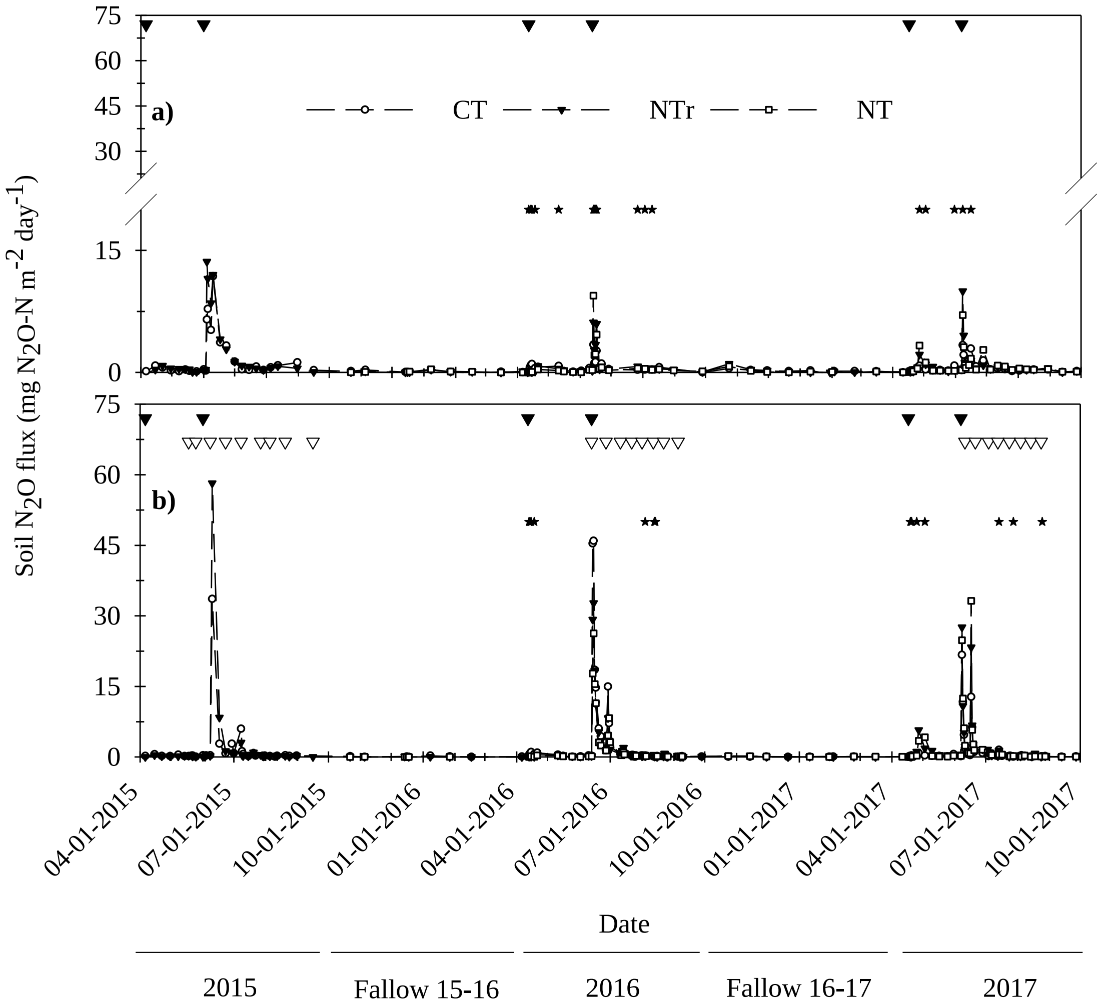

Figure 4. Soil N_2O flux for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining maize stover), NT (no-tillage removing maize stover). *Indicates significant differences between treatments within a date at $p<0.05$. Black triangles indicate fertilizer applications. White triangles indicate flood irrigation events.

Over the entire measurement period, soil tillage did not affect the soil daily N_2O fluxes in neither irrigation systems (Table 4). Throughout the three growing seasons and under S irrigation, soil daily N_2O fluxes presented an average value of 1.09 ± 0.67, 1.50 ± 0.88 and 0.89 ± 0.04 mg N_2O-N m^{-2} day^{-1} for CT, NTr and NT respectively. Meanwhile, for the same period, CT, NTr and NT showed an average value of soil daily N_2O fluxes of 2.09 ± 0.88, 2.39 ± 0.10 and 2.09 ± 0.32, respectively, under F irrigation.

Moreover, soil N_2O flux showed positive exponential relationships with soil temperature at 5 cm depth (Fig. 5a), and total available soil inorganic nitrogen content (nitrate and soil ammonium) at 0-5 cm depth (Fig. 5b) for S and F irrigation systems. These relationships were similar in both irrigation systems, showing a quick increase on soil daily N_2O fluxes when soil temperature was above 20ºC and when the total available soil inorganic nitrogen content increased due to the N fertilizer application, especially during the top dressing application (June).

In addition to the relationships between daily soil N_2O fluxes and soil temperature and total available N, daily soil N_2O fluxes showed a significant relationship with the WFPS for both irrigation systems (Fig. 5c). This positive relationship between soil N_2O fluxes and WFPS were only observed during the pre-planting and top dressing applications of N fertilizers (i.e. 24 h prior and 24, 48 72 and 96 h after N fertilizer application). However, no significant relationship between soil N_2O fluxes and WFPS were observed during the rest of the measurement period. Daily soil N_2O fluxes showed a strong increase when WFPS values were higher than 60% and reaching the highest fluxes at 80% of WFPS. This large impact of the WFPS on the daily soil N_2O fluxes were only observed for F irrigation (black triangles), which resulted in soil N_2O peak fluxes three times higher compared with S irrigation (empty circles) (Fig. 5c).

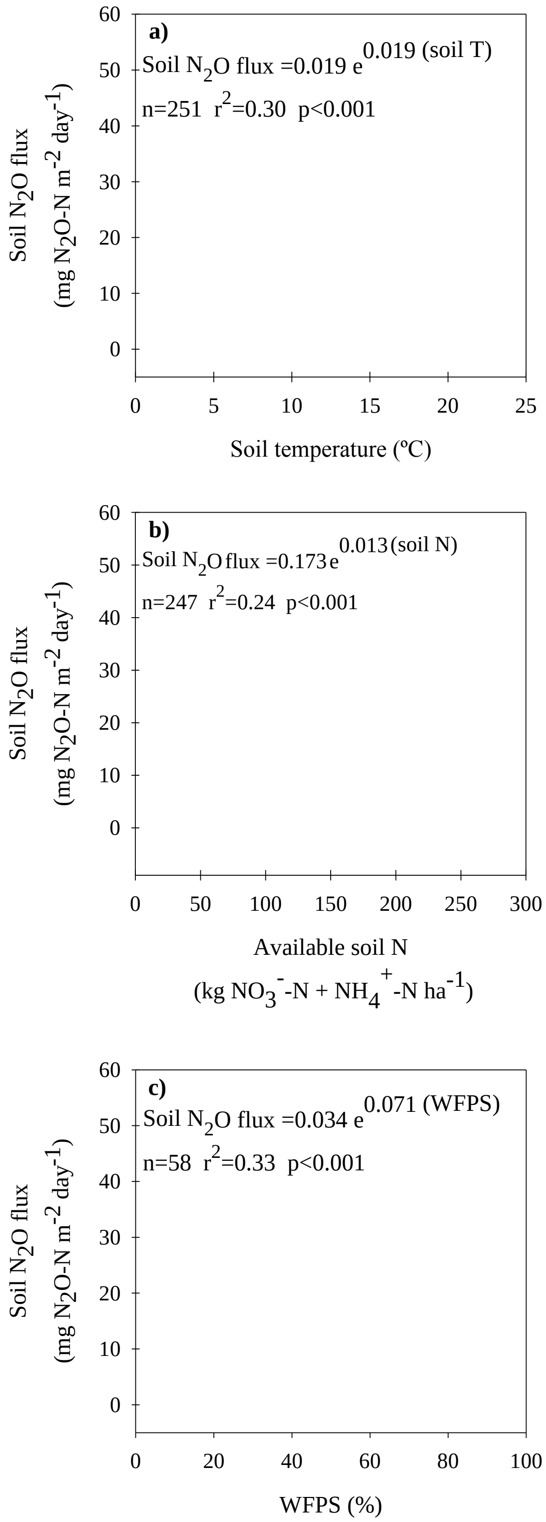

Figure 5. Regression analysis for sprinkler (empty circles) and flood (black triangles) irrigation systems between soil N_2O flux and soil temperature (5 cm depth) (a) for the entire measurement period, available soil inorganic nitrogen content (0-5 cm depth) (b) for the entire measurement period and WFPS (0-5 cm depth) during the N fertilization events. Each point represents the average value of all treatments for each sampling date.

Irrigation system significantly affected cumulative soil N_2O emissions in 2015, 2016 and 2017 (Table 5). In the three growing seasons, S irrigation resulted in a reduction of cumulative N_2O emissions of 34, 51 and 40% for 2015, 2016 and 2017, respectively, compared with F irrigation. Cumulative soil N_2O emissions were not affected significantly by the tillage system nor by its interaction with the irrigation system (Table 5).

Table 5. Cumulative N_2O emissions, for 2015, 2016 and 2017 growing seasons (i.e. April – October) as affected by irrigation system (S, sprinkler; F, flood), soil tillage (CT, conventional tillage, NTr no-tillage with crop stover, NT, no-tillage without crop stover) and their interactions.

Effects and levels†	Cumulative N_2O emissions		
	2015	2016	2017
	kg N_2O-N ha^{-1}		
Irrigation system	*0.019*	*0.003*	*0.018*
S	2.20 ± 0.34 b	0.89 ± 0.21 b	0.95 ± 0.24 b
F	3.33 ± 1.24 a	1.83 ± 0.54 a	1.59 ± 0.56 a
Tillage system	NS	NS	NS
CT	2.30 ± 0.70	1.60 ± 0.86	0.95 ± 0.23
NTr	3.23 ± 1.32	1.40 ± 0.49	1.51 ± 0.74
NT		1.08 ± 0.45	1.34 ± 0.41
Irrigation system x Tillage system	NS	NS	NS
CT-S	2.11 ± 0.42	0.92 ± 0.22	0.81 ± 0.19
NTr-S	2.30 ± 0.30	1.04 ± 0.19	0.97 ± 0.19
NT-S		0.71 ± 0.08	1.06 ± 0.34
CT-F	2.50 ± 0.96	2.28 ± 0.64	1.10 ± 0.18
NTr-F	4.16 ± 0.94	1.76 ± 0.40	2.05 ± 0.68
NT-F		1.45 ± 0.29	1.62 ± 0.29

†For each effect and growing season values followed by different letters are significantly different according to a Tukey test at p=0.05 level. NS, non-significant. *p-values* are given when significant.

Grain yield was differently affected by the irrigation and the tillage system depending on the growing season. In 2015, a significant interaction between irrigation and tillage system was observed, increasing grain yield in the order NTr-S>CT-S=CT-F>NTr-F, with values ranged between 10.15 to 14.34 Mg ha^{-1}. Likewise, the interaction between irrigation and tillage system affected significantly the grain yield in 2016, in which NTr tillage obtained the greatest values under S irrigation (13.26 Mg ha^{-1}) compared with F irrigation (10.21 Mg ha^{-1}) (Table 6). However, in 2017, irrigation and tillage system, but no their interaction, had a significant impact on the grain yield, obtaining the greatest values under S irrigation and CT tillage, 17.08 and 17.00 Mg ha^{-1} respectively.

S irrigation resulted in higher grain N uptake compared with F irrigation over the three growing season (Table 6). In 2015, the interaction between irrigation and tillage system affected grain N-uptake (Table 6). Under sprinkler irrigation, the NTr treatment produced higher N uptake than the CT treatment, but no differences were found between tillage treatments under flood irrigation. (Table 6). In contrast, in 2016 and 2017, irrigation and tillage systems affected the grain N-uptake but not their interaction. CT tillage showed higher grain N-uptake than NTr and NT tillage in 2016, while in 2017 significant differences were only observed between CT and NT tillage (Table 6).

Table 6. Maize grain yield (14% moisture) and maize grain N-uptake, for 2015, 2016 and 2017 growing seasons as affected by irrigation system (S, sprinkler, F, flood), soil tillage (CT, conventional tillage, NTr no-tillage with crop stover, NT, no-tillage without crop stover) and their interactions.

Effects and levels[†]	Grain yield			Grain N-uptake		
	2015	2016	2017	2015	2016	2017
	——— Mg ha^{-1} ———			——— kg ha^{-1} ———		
Irrigation system	*0.002*	NS	*0.012*	*<0.001*	*0.018*	*<0.001*
S	13.60 ± 0.86 a	13.67 ± 1.44	17.08 ± 0.92 a	158 ± 11 a	150 ± 16 a	180 ± 11 a
F	10.78 ± 0.92 b	12.16 ± 1.87	15.23 ± 1.28 b	116 ± 10 b	124 ± 17 b	150 ± 14 b
Tillage system	NS	*<0.001*	*0.029*	NS	*<0.001*	*0.014*
CT	12.13 ± 0.96	14.65 ± 0.61 a	17.00 ± 0.75 a	135 ± 18	154 ± 13 a	178 ± 17 a
NTr	12.25 ± 2.33	11.74 ± 1.99 b	16.13 ± 1.53 ab	139 ± 32	125 ± 25 b	163 ± 17 ab
NT		12.35 ± 1.00 b	15.33 ± 1.56 b		134 ± 13 b	155 ± 22 b
Irrigation system x Tillage system	*0.003*	*0.019*	NS	*0.015*	NS	NS
CT-S	12.85 ± 0.32 b	14.93 ± 0.73 a	17.44 ± 0.37	150 ± 6 b	165 ± 6	191 ± 5
NTr-S	14.34 ± 0.3 a	13.26 ± 1.70 abc	17.13 ± 1.66	168 ± 3 a	144 ± 21	176 ± 13
NT-S		12.82 ± 1.08 bcd	16.65 ± 0.08		142 ± 10	174 ± 9
CT-F	11.41 ± 0.8 b	14.37 ± 0.41 abc	16.56 ± 0.83	121 ± 11 c	143 ± 4	164 ± 11
NTr-F	10.15 ± 0.54 c	10.21 ± 0.09 d	15.13 ± 0.33	111 ± 8 c	103 ± 3	149 ± 5
NT-F		11.89 ± 0.82 cd	14.00 ± 0.91		122 ± 9	136 ± 6

[†]For each effect, growing season and variable the values followed by different letters are significantly different according to Tukey test at p=0.05 level. NS, non-significant. *p-values* are given when significant

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Finally, grain yield N_2O scaled emissions (g N_2O-N Mg^{-1} grain) and grain N-uptake N_2O scaled emissions (g N_2O-N kg^{-1} N grain) were significantly affected by the irrigation system in the three growing seasons, presenting the lowest values under S irrigation compared with F irrigation (Table 7). In the three growing seasons, S irrigation reported a reduction of the grain yield N_2O scaled emissions of 49 (2015), 59 (2016) and 47% (2017) compared with F irrigation. Similarly, the grain N-uptake N_2O scaled emissions showed a decrease of 53, 59 and 51% for 2015, 2016 and 2017, respectively, under S irrigation compared with F irrigation (Table 7).

In 2017, the tillage system showed significant differences for grain yield N_2O scaled emissions and grain N-uptake N_2O scaled emissions, with the greatest values under NTr and NT tillage for both indexes (Table 7). However, in 2015 and 2016, no significant differences were observed neither in grain yield N_2O scaled emissions nor in grain N-uptake N_2O scaled emissions between tillage systems, even when the scaled emissions were almost two times greater under NTr compared with CT as it was observed in the 2015 maize growing season (Table 7).

Table 7. Scaled soil N_2O emissions by maize grain yield and maize grain N-uptake, for 2015, 2016 and 2017 growing seasons as affected by irrigation system (S, sprinkler, F, flood), soil tillage (CT, conventional tillage, NTr no-tillage with crop stover, NT, no-tillage without crop stover) and their interactions.

Effects and levels[†]	Scaled soil N_2O emissions					
	by grain yield			by grain N-uptake		
	2015	2016	2017	2015	2016	2017
	g N_2O-N Mg^{-1} grain			g N_2O-N kg^{-1} grain		
Irrigation system	*0.002*	*<0.001*	*0.015*	*0.009*	*<0.001*	*0.009*
S	162 ± 24 b	66 ± 18 b	56 ± 15 b	13.86 ± 1.91 b	6.00 ± 1.79 b	5.27 ± 1.35 b
F	315 ± 137 a	151 ± 40 a	106 ± 40 a	29.22 ± 12.51 a	14.81 ± 3.81 a	10.72 ± 3.95 a
Tillage system	NS	NS	*0.014*	NS	NS	*0.014*
CT	190 ± 54	109 ± 59	56 ± 17 b	17.19 ± 5.36	10.73 ± 6.30	5.46 ± 1.61 b
NTr	287 ± 157	127 ± 59	96 ± 17 a	25.88 ± 15.09	11.99 ± 5.65	9.58 ± 5.24 a
NT		89 ± 43	90 ± 22 a		8.50 ± 4.37	8.96 ± 3.56 a
Irrigation system x Tillage system	NS	NS	NS	NS	NS	NS
CT-S	163 ± 28	61 ± 12	46 ± 11	13.99 ± 2.26	5.54 ± 8.25	4.26 ± 1.05
NTr-S	161 ± 24	80 ± 25	57 ± 9	13.73 ± 1.98	7.45 ± 10.54	5.50 ± 0.90
NT-S		55 ± 4	64 ± 21		5.01 ± 14.16	6.06 ± 1.69
CT-F	216 ± 66	158 ± 40	66 ± 12	38.04 ± 11.04	15.92 ± 8.60	6.67 ± 1.01
NTr-F	414 ± 116	173 ± 41	135 ± 45	16.53 ± 8.25	16.53 ± 8.25	13.65 ± 4.25
NT-F		123 ± 33	116 ± 21		11.99 ± 11.45	11.86 ± 1.93

[†]For each effect, growing season, and variable the values followed by different letters are significantly different according to Tukey test at p=0.05 level. NS, non-significant. *p-values* are given when significant.

DISCUSSION

In the irrigated Mediterranean conditions evaluated in this study, it has been assessed that irrigation system impacted soil N_2O emission in maize monocropping systems. In similar Spanish conditions, Sanchéz-Martín et al. (2008) obtained soil N_2O fluxes for a furrow-irrigated maize similar to the measured in this work under F irrigation. The higher soil N_2O fluxes found with F irrigation compared to S irrigation in our work were closer to those measured by Omonode et al. (2011) in a non-irrigated maize in Indiana.

Comparing with sprinkler irrigated maize studies, soil N_2O fluxes measured in this work were in the range of values reported by Liu et al. (2005) in Colorado. Under Mediterranean conditions, Sanz-Cobena et al. (2012) reported similar soil N_2O fluxes when they used an irrigation scheduling similar to our work. In contrast, Álvaro-Fuentes et al. (2016), in the same study area, observed soil N_2O fluxes three and ten times lower than the values measured in our study (for S and F irrigation systems, respectively). Differences between studies could be related to the different air sampling protocol used in both studies since in the Álvaro-Fuentes et al. (2016) study did not increase air sampling frequency during the fertilization events. Moreover, these differences in soil N_2O fluxes between both studies could be also related with the high temporal and spatial variability of soil N_2O emissions associated to different factors, such as soil properties, climate, management and microorganism populations (Leip et al., 2011; Venterea et al., 2012).

In 2016 and 2017 but not in 2015 and for both irrigation systems, soil N_2O fluxes were affected by the interaction between soil tillage system and sampling date. This interaction was observed after the fertilizer application events, especially after the top dressing application, when the greatest peak of soil N_2O fluxes occurred as other researchers observed previously (Smith et al., 1997; Shen et al., 2018).

The increase in total available soil nitrogen content (ammonium and nitrate) after N fertilizer applications had an impact on soil N_2O fluxes in both irrigation systems, as it is demonstrated in a relationship shown (Fig. 5b). This relationship agrees with other studies (McSwiney and Robertson, 2005; Hoben et al., 2011; Zhou et al., 2016) which pointed out the key role of N fertilizer applications on the N_2O emitted from the soil (Dobbie and Smith, 2003; Vallejo et al., 2005). Moreover, the soil N_2O flux peaks observed during the top dressing application were related not only with the high N fertilizer rates applied (200 kg N ha^{-1}) but also with the high soil temperatures measured, similar to the observations reported by other authors (Dobbie and Smith, 2001; Zhou et al., 2016). The warmer soil temperature during the top dressing application (June), could lead in more optimal conditions for the production of N_2O by soil microorganisms, favouring a rapidly increase of the soil N_2O fluxes, "pulsing effect", since soil temperature is a key factor that control nitrification, denitrification and nitrifier denitrification processes (Bouwman et al., 2002; Sanchéz-Martín et al., 2008; Butterbach-Bahl et al., 2013).

Soil N_2O peaks measured under F irrigation were 3 to 4 times greater compared to the peaks measured under S irrigation. The difference in soil N_2O peaks between irrigation systems were related to the different WFPS found. Maximum N_2O peak values (observed during top dressing N fertilizer application) were measured under F irrigation when WFPS were between 70 to 80%, considered as the optimum values for N_2O production (Davidson, 1991). However, under S irrigation, WFPS values were always lower than 60%. Therefore, differences in WFPS explained also the higher cumulative N_2O emissions under F irrigation found compared with S irrigation. On average of the three growing seasons studied, S irrigation reduced cumulative soil N_2O emissions by 42% compared with F irrigation.

The large difference found between irrigation systems was in the range of the results reported by Deng et al. (2018), who predicted a reduction of the 38% on soil N_2O emissions for sprinkler-irrigated maize systems compared with surface-irrigated systems in Californian croplands. In two previous meta-analysis for Mediterranean conditions, Cayuela et al. (2017) reported mean cumulative N_2O emission values of 3.7±3.3 kg N_2O-N ha^{-1} for sprinkler irrigation systems, with a mean N application rate of 226±75 kg N ha^{-1}, while Aguilera et al. (2013) estimated 4±2.6 kg N_2O-N ha^{-1} for furrow and sprinkler irrigation systems, with a mean N application rate of 137 kg N ha^{-1}. In our experiment, mean cumulative N_2O emissions over the three growing seasons for the S irrigation system were 63 and 66% lower than the values reported by these authors, respectively. In contrast, neither of the two meta-analysis reported data of cumulative soil N_2O emissions for flood-irrigated maize. Furthermore, values of cumulative soil N_2O emissions for the different tillage systems were in the range of the values estimated by Aguilera et al. (2013) for standard tillage (1.1±1.4 kg N_2O-N ha^{-1}) and minimum tillage (1.9±2.6 kg N_2O-N ha^{-1}). Differences in the emission values found between the two previous meta-analysis and our study were expected since the values obtained in the meta-analyses covered a broad range of different cropping systems, management practices (e.g., N sources and amount, irrigation systems, tillage, etc.) and soil and climate types.

The effect of soil tillage system on soil N_2O emissions varies depending on the study. Some authors reported higher soil N_2O emission under conventional tillage than under no-tillage in different word regions (Halvorson et al., 2008; 2010; Perego et al., 2016), while other showed higher soil N_2O emissions under no-tillage than under conventional tillage systems (Ball et al., 1999; Venterea et al., 2005). Moreover, several researchers found no significant effect of the tillage system on soil N_2O emissions as we observed in this work (Liu et al. 2005; Heller et al.; 2010; Forte et al., 2016). Likewise, stover removal did not impact soil N_2O emissions, similarly to the results reported by others (Guzman et al., 2015; Johnson and Barbour, 2018; Fang et al. (2019). All these studies justified their results based mainly on the effect of soil available N and WFPS on N_2O emissions. In our study, the soil available N content was not significantly different between tillage systems in neither of two irrigation systems over the entire period, fact that could explain the no significant effect of the tillage systems and stover management on the soil N_2O due to the key role of N on the N_2O emissions, as explained previously.

Maize grain yields were in the range of the values reported in other studies performed in the same region (Robles et al., 2017; Cavero et al., 2018). In general, grain yields and grain N uptake in F irrigation plots were 14 and 20% lower respectively, compared with S irrigation plots. Increasing the frequency of irrigation, which only can be easily done with sprinkler irrigation, has been found to increase crop yield because the soil water content is more stable (Rawlins and Raats, 1975). The lower grain yields and grain N uptake under F irrigation could be related with the negative impact of the waterlogging, which occurs during F irrigation after the large amount of irrigation water applied in every irrigation event (80-100 mm). Ren et al. (2016) observed that waterlogging affected the ear formation in maize, reducing ear volume and decreasing sink capacity when maize was under waterlogging conditions at different growth stages. Furthermore, F irrigation is prone to favour plant water stress due to the long periods between consecutive irrigation events. In contrast, higher irrigation frequency under S irrigation provided more stable soil water content (Segal et al., 2006), increasing the availability of water for the plant and avoiding plant water stress.

Furthermore, over the three growing seasons, conventional tillage trended to result in greater grain yield and grain N uptake compared with no-tillage systems. Afzalinia and Zabihi (2014) and Salem et al. (2015) observed similar reductions in crop yields during the first year of implementation of the no-tillage systems for a maize crop under Mediterranean conditions. Several reasons such as waterlogging, poor crop establishment, lower root development by compaction, nutrient deficiencies or time of implementation are pointed out as possible reasons, which would explain the worst crop performance under no-tillage systems (Pittelkow et al., 2015). In our work, the lower mean soil bulk density found in conventional tillage compared with no-tillage systems (1.38, 1.53 and 1.53 for CT, NTr and NT, respectively) would lead to more optimal conditions for the development of maize roots and thus the better crop performance under conventional tillage (Cid et al., 2015).

Grain yield N_2O scaled emissions measured were in the range of the values obtained by Omonode et al. (2015) for a maize crop under conventional tillage and no-tillage systems with a nitrogen application rate of 200 kg N ha^{-1} $year^{-1}$. Likewise, grain N uptake N_2O scaled emissions presented in this work were in the range of values reported by Álvaro-Fuentes et al. (2016) in the same region. For both N_2O scaled emissions, by grain yield and by grain N uptake, irrigation system had a significant impact. The S irrigation system presented lower values compared with the F irrigation system over the three growing seasons studied. The lower cumulative N_2O emissions and the higher grain yields and N-uptake by grain obtained under S irrigation system explained the lower N_2O yield-scaled emissions by grain yield and by N-uptake by grain found. Moreover, in 2017, no-tillage systems resulted in an increment of the N_2O scaled emissions compared with CT tillage mainly due to the decrease in grain yield and grain N-uptake found under no-tillage systems.

CONCLUSIONS

In the Mediterranean conditions studied the irrigation system is an important strategy to reduce soil N_2O emissions. Throughout three maize seasons, the sprinkler irrigation system reduced soil N_2O emissions, and grain yield and grain N uptake N_2O scaled emissions, compared to the flood irrigation system. Sprinkler irrigation is a win-win system for irrigated maize: more grain yield and lower soil N_2O emissions. The soil tillage system affected daily soil N_2O fluxes, especially after the fertilization events, but it had not effect on the seasonal mean soil N_2O emissions. However, no-tillage systems showed a trend to increase the grain yield and grain N uptake N_2O scaled emissions compared to conventional tillage systems when the same amount of water was applied. More information about the performance of no-tillage in irrigated maize monoculture systems is needed to consider no-tillage systems as a mitigation strategy of N_2O emissions under Mediterranean conditions. This work pointed out the importance of an appropriate selection of irrigation and tillage system to minimize soil N_2O emissions in Mediterranean agroecosystems.

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REFERENCES

Afzalinia, S., Zabihi, J., 2014. Soil compaction variation during corn growing season under conservation tillage. Soil Tillage Res. 137, 1-6

Aguilera, E., Lassaletta, L., Sanz-Cobena, A., Garnier, J., Vallejo, A., 2013. The potential of organic fertilizers and water management to reduce N_2O emissions in Mediterranean climate cropping systems. A review. Agric. Ecosyst. Environ. 164, 32–52.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome 300, D05109.

Álvaro-Fuentes, J., Arrúe, J.L., Cantero-Martínez, C., Isla, R., Plaza-Bonilla, D., Quílez, D., 2016. Fertilization scenarios in sprinkler-irrigated corn under mediterranean conditions: effects on greenhouse gas emissions. Soil Sci. Soc. Am. J. 80, 662–671. https://doi.org/10.2136/sssaj2015.04.0156

Ball, B.C., Scott, A., Parker, J.P., 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Tillage Res. 53, 29–39. https://doi.org/10.1016/s0167-1987(99)00074-4

Bateman, E.J., Baggs, E.M., 2005. Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space. Biol. Fertil. Soils 41, 379–388. https://doi.org/10.1007/s00374-005-0858-3

Bent, E., Nemeth, D., Wagner-Riddle, C., Dunfield, K., 2016. Residue management leading to higher field-scale N_2O flux is associated with different soil bacterial nitrifier and denitrifier gene community structures. Appl. Soil Ecol. 108, 288-299.

Blanco-Canqui, H., Lal, R., 2008. Corn stover removal impacts on micro-scale soil physical properties. Geoderma 145, 335-346.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. Global Biogeochem. Cycles 16, 13. https://doi.org/10.1029/2001gb001811

Bremner, J.M., 1997. Sources of nitrous oxide in soils. Nutr. Cycl. Agroecosyst. 49, 7-16.

Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R., Zechmeister-Boltenstern, S., 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philos. Trans. R. Soc. B-Biological Sci. 368, 13. https://doi.org/10.1098/rstb.2013.0122

Cavero, J., Beltrán, A., Aragües, R., 2003. Nitrate exported in drainage waters of two sprinkler-irrigated watersheds. J. Environ. Qual. 32, 916-926.

Cavero, J., Medina, E.T., Montoya, F., 2018. Sprinkler irrigation frequency affects maize yield depending on irrigation time. Agron. J. https://doi.org/10.2134/agronj2018.05.0315

Cayuela, M.L., Aguilera, E., Sanz-Cobena, A., Adams, D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L., Alfaro, M.A., Pappa, V.A., Smith, P., Garnier, J., Billen, G., Bouwman, L., Bondeau, A., Lassaletta, L., 2017. Direct nitrous oxide emissions in Mediterranean climate cropping systems: Emission factors based on a meta-analysis of available measurement data. Agric. Ecosyst. Environ. 238, 25–35. https://doi.org/10.1016/j.agee.2016.10.006

Cid, P., Carmona, I., Murillo, J.M., 2014. No-tillage permanent bed planting andcontrolled traffic in a maize-cotton irrigated system under

Mediterraneanconditions: effects on soil compaction, crop performance and carbonsequestration. Eur. J. Agron. 61, 24–34.

Davidson EA (1991) Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: Microbial Production and Consumption of Greenhouse Gases (eds Rogers JE, Whitman WB), pp. 219–235. American Society of Microbiology, Washington, DC.

Davidson, E.A., Keller, M., Erickson, H.E., Verchot, L.V., Veldkamp, E., 2000. Testing a conceptual model of soil emissions of nitrous and nitric oxides. Bioscience 50, 667-680. https://doi.org/1010.1641/00063568(2000)050[0667:TACMOS]2.0.CO;2

Dastane, N.G. 1978. Effective rainfall in irrigated agriculture. Irrigation and Drainage Paper 25. FAO, Rome.

Deng, J., Guo, L., Salas, W., Ingraham, P., Charrier-Klobas, J.G., Frolking, S., Li, C.S., 2018. Changes in irrigation practices likely mitigate nitrous oxide emissions from california cropland. Glob. Biogeochem. Cycle 32, 1514-1527.

Dobbie, K.E., Smith, K.A., 2001. The effects of temperature, water-filled pore space and land use on N_2O emissions from an imperfectly drained gleysol. Eur. J. Soil Sci. 52, 667-673.

Dobbie, K.E., Smith, K.A., 2003. Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. Glob. Chang. Biol. 9, 204–218. https://doi.org/10.1046/j.1365-2486.2003.00563.x

Fan, J.L., Luo, R.Y., Liu, D.Y., Chen, Z.M., Luo, J.F., Boland, N., Tang, J.W., Hao, M.D., McConkey, B., Ding, W.X., 2018. Stover retention rather than no-till decreases the global warming potential of rainfed continuous maize cropland. Field Crop. Res. 219, 14-23.

Firestone, M.K., Davidson, E.A., 1989. Microbial basis of NO and N_2O production and consumption in soil. In: Andreae, M.O., Schimel, D.S. (Eds.), Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere. John Wiley & Sons, Chichester, UK, pp. 7–21.

Forte, A., Fiorentino, N., Fagnano, M., Fierro, A., 2017. Mitigation impact of minimum tillage on CO2 and N_2O emissions from a Mediterranean maize cropped soil under low-water input management. Soil Tillage Res. 166, 167-178.

Grossman R, Reinsch T., 2002. Bulk density and linear extensibility. In: Dane JH, ToppGC (eds) Methods of soil analysis. Part 4. Physical methods. ASA, SSSA, Madison,WI, 201–228

Guzman, J., Al-Kaisi, M., Parkin, T., 2015. Greenhouse gas emissions dynamics as influenced by corn residue removal in continuous corn system. Soil Sci. Soc. Am. J. 79, 612-625.

Hoben, J.P., Gehl, R.J., Millar, N., Grace, P.R., Robertson, G.P., 2011. Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. Glob. Change Biol. 17, 1140-1152.

Halvorson, A.D., Del Grosso, S.J., Alluvione, F., 2010. Tillage and inorganic nitrogen source effects on nitrous oxide emissions from irrigated cropping systems. Soil Sci. Soc. Am. J. 74, 436-445.

Halvorson, A.D., Del Grosso, S.J., Reule, C.A., 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. J. Environ. Qual. 37, 1337-1344.

Heller, H., Bar-Tal, A., Tamir, G., Bloom, P., Venterea, R.T., Chen, D., Zhang, Y., Clapp, C.E., Fine, P., 2010. Effects of manure and cultivation on carbon dioxide and nitrous oxide emissions from a corn field under mediterranean conditions. J. Environ. Qual. 39, 437-448.

Hutchinson, G.L., Mosier, A.R., 1981. Improved soil cover method for field measurement of nitrous-oxide fluxes. Soil Sci. Soc. Am. J. 45, 311–316. https://doi.org/10.2136/sssaj1981.03615995004500020017x

IPCC. 2014. Climate Change 2014 Synthesis Report.

Jin, V.L., Schmer, M.R., Stewart, C.E., Sindelar, A.J., Varvel, G.E., Wienhold, B.J., 2017. Long-term no-till and stover retention each decrease the global warming potential of irrigated continuous corn. Glob. Change Biol. 23, 2848-2862.

Johnson, J.M.F., Barbour, N.W., 2019. Stover harvest did not change nitrous oxide emissions in two minnesota fields. Agronomy Journal 111, 143-155.

Kiniry, J.R. 1991. Maize phasic development. In: J. Hanks and J.T. Ritchie, editors, Modeling plant and soil systems. Agron. Mongr. 31. ASA, CSA, and SSSA, Madison, WI. 55–70.

Lecina, S., Isidoro, D., Playán, E., Aragües, R., 2010. Irrigation modernization in spain: effects on water quantity and quality-a conceptual approach. Int. J. Water Resour. Dev. 26, 265–282. https://doi.org/10.1080/07900621003655734

Leip, A., Busto, M., Winiwarter, W., 2011. Developing spatially stratified N_2O emission factors for Europe. Environ. Pollut. 159, 3223–3232. https://doi.org/10.1016/j.envpol.2010.11.024

Levy, P.E., Cowan, N., van Oijen, M., Famulari, D., Drewer, J., Skiba, U., 2017. Estimation of cumulative fluxes of nitrous oxide: uncertainty in temporal upscaling and emission factors. Eur. J. Soil Sci. 68, 400–411. https://doi.org/10.1111/ejss.12432

Linn, D.M., Doran, J.W., 1984. Effect of water-filled pore-space on carbon-dioxide and nitrous-oxide production in tilled and nontilled soils. Soil Sci. Soc. Am. J. 48, 1267–1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x

Liu, X.J., Mosier, A.R., Halvorson, A.D., Zhang, F.S., 2005. Tillage and nitrogen application effects on nitrous and nitric oxide emissions from irrigated corn fields. Plant Soil 276, 235–249

Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente. 2017a. Encuesta sobre superficies y rendimientos. Análalis de las técnicas de mantenimiento del suelo y de los métodos de siembra en España. Subdirección General de Estadística. Secretaría General Técnica. MAPAMA, Madrid.

Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente. 2017b. Encuesta sobre superficies y rendimientos. Informe sobre regadíos en España. Subdirección General de Estadística. Secretaría General Técnica. MAPAMA, Madrid.

Maris, S.C., Lloveras, J., Vallejo, A., Teira-Esmatges, M.R., 2018. Effect of stover management and nitrogen fertilization on n_2o and co_2 emissions from irrigated maize in a high nitrate mediterranean soil. Water Air Soil Pollut. 229, 17. https://doi.org/10.1007/s11270-017-3660-6

Martínez-Cob, A., Playán, E., Zapata, N., Cavero, J., Medina, E.T., Puig, M., 2008. Contribution of evapotranspiration reduction during sprinkler irrigation to application efficiency. J. Irrig. Drain. Eng. 134, 745–756. https://doi.org/10.1061/(asce)0733-9437(2008)134:6(745)

McSwiney, C.P., Robertson, G.P., 2005. Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system. Glob. Chang. Biol. 11, 1712–1719. https://doi.org/10.1111/j.1365-2486.2005.01040.x

Omonode, R.A., Kovacs, P., Vyn, T.J., 2015. Tillage and nitrogen rate effects on area- and yield-scaled nitrous oxide emissions from pre-plant anhydrous ammonia. Agron. J. 107, 605–614. https://doi.org/10.2134/agronj14.0440

Omonode, R.A., Smith, D.R., Gal, A., Vyn, T.J., 2011. Soil nitrous oxide emissions in corn following three decades of tillage and rotation treatments. Soil Sci. Soc.

Perego, A., Wu, L., Gerosa, G., Finco, A., Chiazzese, M., Amaducci, S., 2016. Field evaluation combined with modelling analysis to study fertilizer and tillage as factors affecting N_2O emissions: A case study in the Po valley (Northern Italy). Agric. Ecosyst. Environ. 225, 72-85.

Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X.Q., van Groenigen, K.J., Lee, J., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. Field Crop. Res. 183, 156-168

Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manag. 80, 100–116.

Plaza-Bonilla, D., Alvaro-Fuentes, J., Arrue, J.L., Cantero-Martinez, C., 2014. Tillage and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed Mediterranean area. Agric. Ecosyst. Environ. 189, 43–52.

Plaza-Bonilla, D., Alvaro-Fuentes, J., Bareche, J., Pareja-Sanchez, E., Justes, E., Cantero-Martinez, C., 2018. No-tillage reduces long-term yield-scaled soil nitrous oxide emissions in rainfed Mediterranean agroecosystems: A field and modelling approach. Agric. Ecosyst. Environ. 262, 36–47. https://doi.org/10.1016/j.agee.2018.04.007

Rawlins, S.L., Raats, P.A.C., 1975. Prospects for high-frequency irrigation. Science 188, 604-610. https://doi.org/10.1126/science.188.4188.604

Reay, D.S., Davidson, E.A., Smith, K.A., Smith, P., Melillo, J.M., Dentener, F., Crutzen, P.J., 2012. Global agriculture and nitrous oxide emissions. Nat. Clim. Chang. 2, 410. https://doi.org/10.1038/NCLIMATE1458

Ren, B., Zhang, J., Dong, S., Liu, P., Zhao, B., 2016. Effects of duration of waterlogging at different growth stages on grain growth of summer maize (zea mays l.) Under field conditions. J. Agron. Crop Sci. 202, 564-575.

Robles, O., Playan, E., Cavero, J., Zapata, N., 2017. Assessing low-pressure solid-set sprinkler irrigation in maize. Agric. Water Manag. 191, 37–49.

Salem, H.M., Valero, C., Munoz, M.A., Rodriguez, M.G., Silva, L.L., 2015. Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. Geoderma 237, 60-70.

Sanchéz-Martín, L., Arce, A., Benito, A., Garcia-Torres, L., Vallejo, A., 2008. Influence of drip and furrow irrigation systems on nitrogen oxide emissions from a horticultural crop. Soil Biol. Biochem. 40, 1698-1706.

Sanz-Cobena, A., Sanchéz-Martín, L., Garcia-Torres, L., Vallejo, A., 2012. Gaseous emissions of N_2O and NO and NO_3^- leaching from urea applied with urease and nitrification inhibitors to a maize (Zea mays) crop. Agric. Ecosyst. Environ. 149, 64-73.

Sanz-Cobena, A., Lassaletta, L., Aguilera, E., del Prado, A., Garnier, J., Billen, G., Iglesias, A., Sanchez, B., Guardia, G., Abalos, D., Plaza-Bonilla, D., Puigdueta-

Bartolome, I., Moral, R., Galan, E., Arriaga, H., Merino, P., Infante-Amate, J., Meijide, A., Pardo, G., Álvaro-Fuentes, J., Gilsanz, C., Baez, D., Doltra, J., Gonzalez-Ubierna, S., Cayuela, M.L., Menendez, S., Diaz-Pines, E., Le-Noe, J., Quemada, M., Estelles, F., Calvet, S., van Grinsven, H.J.M., Westhoek, H., Sanz, M.J., Gimeno, B.S., Vallejo, A., Smith, P., 2017. Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. Agric. Ecosyst. Environ. 238, 5–24. https://doi.org/10.1016/j.agee.2016.09.038

SAS Institute Inc (2012) Using JMP 10. SAS Institute, Cary, NC

Sauer, T.J., Hatfield, J.L., Prueger, J.H., Norman, J.M., 1998. Surface energy balance of a corn residue-covered field. Agric. For. Meteorol. 89, 155-168.

Segal, E., Ben-Gal, A., Shani, U., 2006. Root water uptake efficiency under ultra-high irrigation frequency. Plant Soil 282, 333-341.

Shen, Y.W., Sui, P., Huang, J.X., Wang, D., Whalen, J.K., Chen, Y.Q., 2018. Global warming potential from maize and maize-soybean as affected by nitrogen fertilizer and cropping practices in the North China Plain. F. Crop. Res. 225, 117–127. https://doi.org/10.1016/j.fcr.2018.06.007

Smith, K.A., McTaggart, I.P., Tsuruta, H., 1997. Emissions of N_2O and NO associated with nitrogen fertilization in intensive agriculture, and the potential for mitigation. Soil Use Manag. 13, 296–304. https://doi.org/10.1111/j.1475-2743.1997.tb00601.x

Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., Baumecker, M., 2013. Irrigation, soil organic carbon and N_2O emissions. A review. Agron. Sustain. Dev. 33, 733-749.

Ussiri, D.A.N., Lal, R., Jarecki, M.K., 2009. Nitrous oxide and methane emissions from long-term tillage under a continuous corn cropping system in Ohio. Soil Tillage Res. 104, 247–255.

Vallejo, A., García-Torres, L., Diez, J.A., Arce, A., Lopez-Fernandez, S., 2005. Comparison of N losses (NO_3^-, N_2O, NO) from surface applied, injected or amended (DCD) pig slurry of an irrigated soil in a Mediterranean climate. Plant Soil 272, 313–325. https://doi.org/10.1007/s11104-004-5754-3

van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., van Groenigen, K.J., 2013. Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. Glob. Chang. Biol. 19, 33–44. https://doi.org/10.1111/j.1365-2486.2012.02779.x

Venterea, R.T., Burger, M., Spokas, K.A., 2005. Nitrogen oxide and methane emissions under varying tillage and fertilizer management. J. Environ. Qual. 34, 1467–1477. https://doi.org/10.2134/jeq2005.0018

Venterea, R.T., Halvorson, A.D., Kitchen, N., Liebig, M.A., Cavigelli, M.A., Del Grosso, S.J., Motavalli, P.P., Nelson, K.A., Spokas, K.A., Singh, B.P., Stewart, C.E., Ranaivoson, A., Strock, J., Collins, H., 2012. Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. Front. Ecol. Environ. 10, 562–570.

Venterea, R.T., Maharjan, B., Dolan, M.S., 2011. Fertilizer source and tillage effects on yield-scaled nitrous oxide emissions in a corn cropping system. J. Environ. Qual. 40, 1521–1531. https://doi.org/10.2134/jeq2011.0039

Zhou, W.J., Ji, H.L., Zhu, J., Zhang, Y.P., Sha, L.Q., Liu, Y.T., Zhang, X., Zhao, W., Dong, Y.X., Bai, X.L., Lin, Y.X., Zhang, J.H., Zheng, X.H., 2016. The effects of nitrogen fertilization on N_2O emissions from a rubber plantation. Sci. Rep. 6, 12. https://doi.org/10.1038/srep28230